Asset Management Framework for Geotechnical Infrastructure

Kristen L. Sanford Bernhardt[1]; J. Erik Loehr[2]; and Daniel Huaco[3]

Abstract: A significant limitation of current asset management systems is lack of consideration of geotechnical issues. This paper presents a simple framework for managing geotechnical facilities using asset management principles. The framework is based on mapping a previously developed generic framework proposed by the Federal Highway Administration with consideration given to several unique aspects of geotechnical structures, the roles these assets play in the transportation infrastructure, and the interaction among "geotechnical assets" and other types of assets such as pavements and bridges. The paper discusses several unique issues that arise when applying asset management principles to geotechnical facilities and presents recommendations for future work to facilitate and improve implementation of such a system. Examples for specific application to maintenance of highway embankments and slopes are provided throughout the paper to illustrate implementation.

DOI: 10.1061/(ASCE)1076-0342(2003)9:3(107)

CE Database subject headings: Infrastructure; Geotechnical engineering; Decision making; Decision support systems; Highway maintenance; Roadside maintenance.

Introduction

For most people, the term "transportation assets" brings to mind physical facilities such as pavements, bridges, and perhaps railway track. However, all of these transportation assets rest (literally) on geotechnical assets, and the performance and costs of more traditional assets are tied, directly or indirectly, to the performance of geotechnical assets. While asset management has become a buzzword for transportation agencies, most of the schemes presented have not included geotechnical assets explicitly.

This paper discusses the "What?" and "Why?" of managing geotechnical assets and describes development of a framework that addresses "How?" geotechnical assets should be managed. It also reviews previous work performed to facilitate effective decision making for geotechnical problems. The paper presents a framework for asset management, followed by a mapping of this generic framework to geotechnical asset management. A number of issues that arise when applying the generic framework to geotechnical assets are then discussed, and a simple approach for implementing the geotechnical framework is introduced for the case of highway embankments and slopes. Finally, we describe several critical issues that must be addressed before the framework can be fully implemented and provide suggestions for future work.

What are Geotechnical Assets and Why Should They be Managed?

Two questions that arise when considering development of a framework for managing geotechnical assets are "What are geotechnical assets?" and "Why should they be managed?" The answer to the first question is not simple, due to the intimate relation between geotechnical assets and other types of assets. The boundaries between geotechnical assets and other types of assets often are blurred. Table 1 shows a collection of assets that we have classified as geotechnical assets. The assets are categorized in terms of function as "exclusively geotechnical," "partially geotechnical," and "minimally geotechnical" to indicate the degree of interaction with other assets. The table also includes the general purpose of each asset and fundamental performance objectives.

Perhaps the type of asset that is most clearly geotechnical is highway embankments and slopes. While one could potentially include these within "real estate" or "right-of-way," few would argue that embankments and slopes are not geotechnical structures. Furthermore, the value of these structures to the transportation system is more than the value of the land alone, since they are essentially "earthen bridges" intended to maintain appropriate roadway alignment. Embankments and slopes are designed almost exclusively by geotechnical or geological engineering professionals, and the "performance" of these structures is generally defined exclusively by the response of the geologic materials to environmental and loading conditions. Highway embankments and slopes interact with other assets in an indirect manner in the sense that most do not directly apply load to, or support, other assets.

[1]Assistant Professor, Dept. of Civil and Environmental Engineering, Lafayette College, 310 AEC, Easton, PA 18042. E-mail: sanfordk@lafayette.edu

[2]Assistant Professor, Dept. of Civil and Environmental Engineering, Univ. of Missouri-Columbia, E2509 Engineering Building East, Columbia, MO 65211-2200. E-mail: eloehr@missouri.edu

[3]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Univ. of Missouri-Columbia, E2509 Engineering Building East, Columbia, MO 65211-2200.

Note. Associate Editor: Sue McNeil. Discussion open until February 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 24, 2002; approved on April 24, 2003. This paper is part of the ***Journal of Infrastructure Systems***, Vol. 9, No. 3, September 1, 2003. ©ASCE, ISSN 1076-0342/2003/3-107–116/$18.00.

Table 1. Summary of Highway Components That May Be Considered Geotechnical Assets

Asset function category	Interaction with other assets	Asset	Purpose	Performance objectives
Exclusively geotechnical	Indirect	Embankments and slopes	To provide for gradual grade changes in vertical alignment	Provide satisfactory support for roadway without intruding on pavement or other transportation structures
Partially geotechnical	Direct	Tunnels and earth retaining structures	To retain earthen materials so that highway can be constructed in restricted right-of-way	Satisfactorily retain earthen materials to prevent intrusion or damage to highway structures
		Culverts and drainage channels	To provide control of surface waters	Prevent accumulation of water on pavement and prevent damage to highway structures from erosion
		Foundations	To transmit structural loads to supporting ground	Satisfactorily support structure without excessive deformations
Minimally geotechnical	Direct	Pavement subgrade	To serve as foundation for pavement	Satisfactorily support pavement without damaging or reducing the life of the pavement

In contrast, the assets listed as partially geotechnical are tied much more directly to other assets in both a physical and conceptual sense. Tunnels, earth retaining structures, and foundations may be considered by some to be ''structural assets'' rather than geotechnical assets, because their performance is likely to be judged from a structural perspective. Design of these structures involves significant structural engineering in addition to geotechnical engineering. Similarly, culverts and drainage channels could be considered ''hydraulic assets,'' because their performance is likely to be judged from the hydraulic perspective, and their design is likely to be performed by hydraulic and structural engineers in addition to geotechnical engineers. However, the performance of these assets is closely linked to the surrounding geologic materials. As such, they reasonably may be considered geotechnical assets.

The third class of assets listed is considered minimally geotechnical. Perhaps the best example of this category of assets is pavement subgrades. While the underlying geologic materials dramatically impact the performance of a pavement system, responsibility for dealing with subgrade quality lies primarily with pavement design professionals. Little input from geotechnical or geological engineering professionals is required beyond site characterization and determination of engineering properties. As a result, pavement subgrades are more likely to be considered within the scope of pavement assets than as geotechnical assets, although the link between the two is apparent.

Regardless of how one chooses to categorize the assets presented in Table 1, clearly, the performance of the assets shown is intimately tied to, and in some cases dominated by, the response of geologic materials to the environmental conditions and loads imposed. It is very likely that what are and are not considered geotechnical assets may vary among organizations according to the organizational structure and history of the organization. Nevertheless, it is useful to try to classify the assets in some form, not for the purpose of ''claiming ownership,'' but rather to highlight the interactions among these assets. The intent of this paper is to raise and address issues associated with management of geotechnical assets in general, regardless of how they are defined. The framework presented in this paper can be used regardless of how one chooses to classify the assets.

The second question, ''Why should geotechnical assets be managed?'' is addressed more easily. The primary reason for managing geotechnical assets is to reduce the life-cycle costs associated with constructing and maintaining these assets at the system-wide level. For example, in the case of highway embankments and slopes, departments of transportation (DOTs) across the country are faced annually with the task of repairing numerous surficial slope failures, commonly referred to as nuisance slides, in addition to more substantial landslides. While often small in size and benign in appearance, these nuisance slides do present significant hazards including damage to or loss of pavement sections, loss or reduced effectiveness of guardrails and other safety measures, blocking of drainage channels, and potential damage to bridges and other structures due to loss of ground support or additional loads imposed by sliding soil and rock. Consequently, small slides require routine maintenance that presents a significant staff and economic burden to infrastructure agencies. While the costs associated with repairing a single slide are often relatively low, total costs associated with repair of large numbers of slides may be extremely high. The Transportation Research Board (TRB) estimated that cumulative annual costs for repair of nuisance slides may exceed cumulative costs for repair of major landslides (Turner and Schuster 1996), which suggests that a conservative estimate of annual repair costs for nuisance slides would exceed $100 million.

The nuisance slide problem shares many characteristics with other asset management problems. Because the problem is widespread, decision makers are often faced with the daunting task of selecting which slides should be repaired within limited construction and maintenance budgets. The problem is complicated by the fact that a wide variety of techniques are available for stabilization and repair of slope failures. The techniques range from simply replacing the failed material back on the slope and regrading, to installation of extensive drainage measures or a complete earth retaining structure. However, the costs and the long-term effectiveness of alternative repair measures vary dramatically, both overall and on a case-by-case basis.

While much work has been performed to develop guidelines on how to prevent, identify, and repair slides (e.g., Klinedinst et al. 1986; Hopkins et al. 1988), only limited procedural assistance is available to help decision makers determine whether, when, or how a slope failure should be repaired so that limited funds are applied where the most benefit will be gained (on a life-cycle basis). One impediment to development of such assistance is that the economics of constructing and maintaining transportation slopes and embankments are not well understood. For example, it is reasonable to conjecture that many slopes are simply too steep and that constructing flatter slopes would reduce long-term maintenance costs. However, the prevailing perception is that the life-cycle costs for routinely maintaining and repairing nuisance slides are smaller than the costs associated with acquiring the additional right-of-way and materials for flatter slopes. Alternatively, repetitive application of an inexpensive but temporarily effective stabilization measure, such as regrading, may be most economical, despite the recurring nature of the activity. Current record keeping of maintenance costs is generally poor (Klinedinst et al. 1986; Hopkins et al. 1988; Turner and Schuster 1996), however, so evaluation of the accuracy of this perception is difficult. An asset management approach that includes consideration of these issues clearly has the potential to improve decision making and reduce overall costs.

A second and perhaps equally important reason for managing geotechnical assets is to facilitate recognition of geotechnical infrastructure as having value to the transportation system. Highway embankments, retaining structures, and other geotechnical structures can be considered ancillary to the actual pavements, because alone they do not directly provide the primary service required of the transportation system. However, few would argue that the transportation system would be possible without them, so their inherent value is understood, if often overlooked. While valuation of geotechnical assets is not a simple issue, failure to recognize and quantify the value of geotechnical infrastructure can lead to increased life-cycle costs for all forms of transportation infrastructure. Reducing these life-cycle costs is one of the goals of asset management.

Geotechnical Decision Support Systems

Work performed to develop specific systems and methods that facilitate effective decision making for geotechnical problems has been sparse, although some efforts have recently been made to improve the situation. This section briefly reviews these efforts, and subsequent portions of this paper discuss the relationship between these systems and asset management systems.

Adams et al. (1988) describe early work in which an expert system is used to provide decision support for retaining wall rehabilitation. Perhaps the most comprehensive set of management systems developed to date are the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) systems developed by the U.S. Army Corps of Engineers (USACE). McKay et al. (1999) describe the development of a uniform condition index (CI) for assessing performance of a variety of types of infrastructure, notably including examples of steel sheet pile structures. These systems were, in large part, developed for structures and applications with acute consequences and often an altogether different level of hazard/risk (e.g., dams) as compared to more common transportation-related geotechnical structures. Nevertheless, these systems provide concepts and models that can be adapted to specific characteristics of transportation infrastructure.

In the more specific area of geotechnical transportation infrastructure, the methods receiving the most attention to date have been those intended to improve decision making for maintenance and rehabilitation of highway embankments and slopes. Perhaps the best developed and most widely utilized system for supporting transportation-related geotechnical decision making is the Rockfall Hazard Rating System (RHRS), which was developed by the Oregon Department of Transportation in collaboration with other state and federal transportation agencies (Pierson and Vickle 1993). The intent of the RHRS, and subsequent revisions, is to reduce systematically the risk of rockfalls and landslides impacting the roadway on a system-wide level by prioritizing sites according to the level of hazard. RHRS uses a six-step process that includes

1. An inventory of all hazardous rockfall sites in the system,
2. Preliminary rating of all sites according to hazard potential,
3. Detailed rating of the highest priority sites identified in Step 2,
4. Preliminary design and cost estimates of remedial measures for the highest priority sites,
5. Project identification and development based on the results of the detailed ratings and estimated costs, and
6. Annual review and updating of the condition of the inventory.

RHRS uses a database to manage all rockfall locations, detailed ratings, and preliminary designs and cost estimates. More recently, the RHRS was incorporated into a more comprehensive, but similar, management program that considers both soil and rock sites (ODOT 2001). This revised system incorporates economic considerations by applying multiplicative ‘‘factors’’ to account for relative repair and user costs among different sites to determine an overall rating.

Several other similar systems have been developed, although to a lesser degree. Ho and Norton (1991) describe the development of an ‘‘unstable slope management system’’ for the Washington State Department of Transportation that can be used to prioritize unstable slope sites. The Eastern Federal Lands Highway Division (EFLHD) of the FHWA developed a landslide rating system to evaluate and rate landslides from a technical standpoint for the Blue Ridge Parkway. More recently, the Kentucky Transportation Center is developing a state-of-the-art geographic information system (GIS) based database for the Kentucky Transportation Cabinet that includes the RHRS in addition to a landslide data and management system and other data management and design tools (Hopkins et al. 2001). Similar activities are being undertaken by the departments of transportation in New Hampshire (Fish and Lane 2002), New York (Hadjin 2002), and North Carolina (Kuhne 2002).

The primary goal of each of the systems described is to produce a prioritized ranking of soil or rock slopes based on the general hazards associated with a particular site. In the sense that the systems are intended to prioritize rehabilitation activities, they share similar goals with asset management systems. However, the systems differ from asset management systems in several respects. The most significant difference is that the existing systems are primarily ‘‘once and for all’’ systems, in that the highest priority sites are expected to be completely repaired (effectively eliminating the hazard), with little explicit consideration given to life-cycle costs and the possibility that repetitive application of temporary stabilization measures may be more cost effective from an organizational perspective. While economic considerations are implicitly included in each of the systems, the level of hazard serves as the primary basis of the rankings. As such, the systems are essentially ‘‘worst-first’’ systems; sites in the worst condition are expected to be rehabilitated first. While this approach is common and may be justified, given that safety is of paramount importance, it is not necessarily the most effective approach from an asset management perspective. In this sense, these existing systems are really hazard assessment and management systems that focus on preventing catastrophic failures within limited funding constraints, whereas an asset management system focuses on cost-effective management of all features, whether or not failure would be catastrophic.

As an example, consider a high priority rock cut with significant potential for producing rockfalls. One approach to remedy the situation might be to install a barrier to prevent the rockfalls from reaching the roadway. An alternative may be to perform scaling on the slope to remove loose materials that have a high probability of falling. The barrier approach is likely to have a higher cost than the scaling alternative, particularly since maintenance crews will have to routinely clear the catchment area to maintain the effectiveness of the repair. However, the scaling approach may be effective only temporarily, because weathering may lead to additional material becoming loose and producing fall hazards. The barrier alternative is likely to have higher initial costs and relatively well-defined but long-term maintenance costs. Conversely, the scaling alternative is likely to have lower initial costs, but the effective life of the repair is uncertain, and it is likely that reapplication of the repair will be needed at some time in the future. Similar dilemmas exist for other geotechnical problems. None of the current ''hazard assessment'' systems is well suited to dealing with such dilemmas. An asset management approach can facilitate better decision making when confronted with such situations. Current systems do address some of the key asset management issues such as data collection, inventory, and condition assessment, however, so they can serve as building blocks for further development of asset management based approaches.

Asset Management

Asset management has been defined in a number of ways; however, the Federal Highway Administration's (FHWA's) Office of Asset Management put forth the following definition in its *Asset Management Primer* (FHWA 1999):

> Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning (FHWA 1997).

The foundation for asset management lies with the goals and objectives of the agency. Asset management then becomes a means for helping an agency to achieve its goals. For example, an agency goal may be ''to provide the public with smooth pavement.'' A corresponding objective may be that no more than 25% of pavements should be rated less than 4 on a five-point scale. The data and analysis tools of an asset management system can guide the agency in determining the investments that should be made in the system to achieve the objective. In a nutshell, ''The fundamental objective is to maximize benefits for users while minimizing agency costs'' (FHWA 1999). The FHWA and the American Association of State Highway and Transportation Officials (AASHTO) are focusing on asset management as a tool for strategic level administration.

A number of schematics for the structure of an asset management system have been proposed. Perhaps the best known is the ''generic'' framework that appears in the *Primer* (Fig. 1). The components of the framework, which are discussed in greater detail subsequently, include the goals discussed previously, data and analysis modules, reporting modules, and feedback mechanisms. One element that is not explicitly included in the FHWA framework but is receiving significant attention is valuation of assets (Cowe Falls et al. 2001). Current interest in asset valuation stems both from a feeling by some that an agency should invest in its assets in proportion to their value, and from a recent change in generally accepted accounting standards for government agencies.

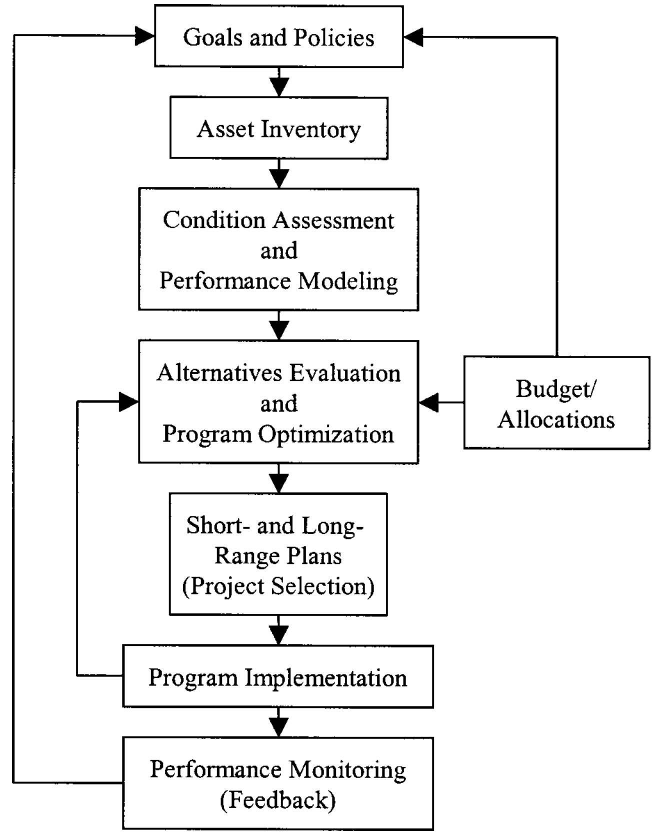

Fig. 1. FHWA ''generic asset management system components''

Although the concept of formalized asset management is relatively new to the public sector, infrastructure management systems, designed for specific asset classes, have existed for several decades. Researchers began with the development of pavement management systems (PMS) in the 1960s and 1970s. In the 1980s, these concepts were applied to develop bridge management systems (BMS). With the success of PMS and BMS, as well as maintenance management systems (MMS), agencies are beginning to explore opportunities for linking the existing systems and for developing systems for other types of infrastructure. For example, the U.S. Army Corps of Engineers' suite of infrastructure management systems includes buildings (BUILDER), rail (RAILER), and pavements (PAVER), as well as locks, dams, and other facilities. The geotechnical decision support systems discussed in previous sections of this paper apply some of the same concepts, although they have not been called ''infrastructure management systems.'' Recently, the U.S. Department of Transportation announced an initiative to develop a tunnel management system for use by state and local agencies in maintaining their highway and transit tunnels (FHWA 2001).

Although most states have some form of PMS or BMS (GAO/RCED 1997; McNeil et al. 2000), the systems are not necessarily used to their full capabilities. According to the *Asset Management Primer*, ''Most states limit application of their management systems to monitoring conditions and then plan and program their projects on a 'worst-first' basis'' (FHWA 1999). In addition, most infrastructure management systems have been developed in isolation from one another; they typically do not share a common database or communicate with one another. The isolation of these ''stovepipe'' systems as well as the typical institutional structure,

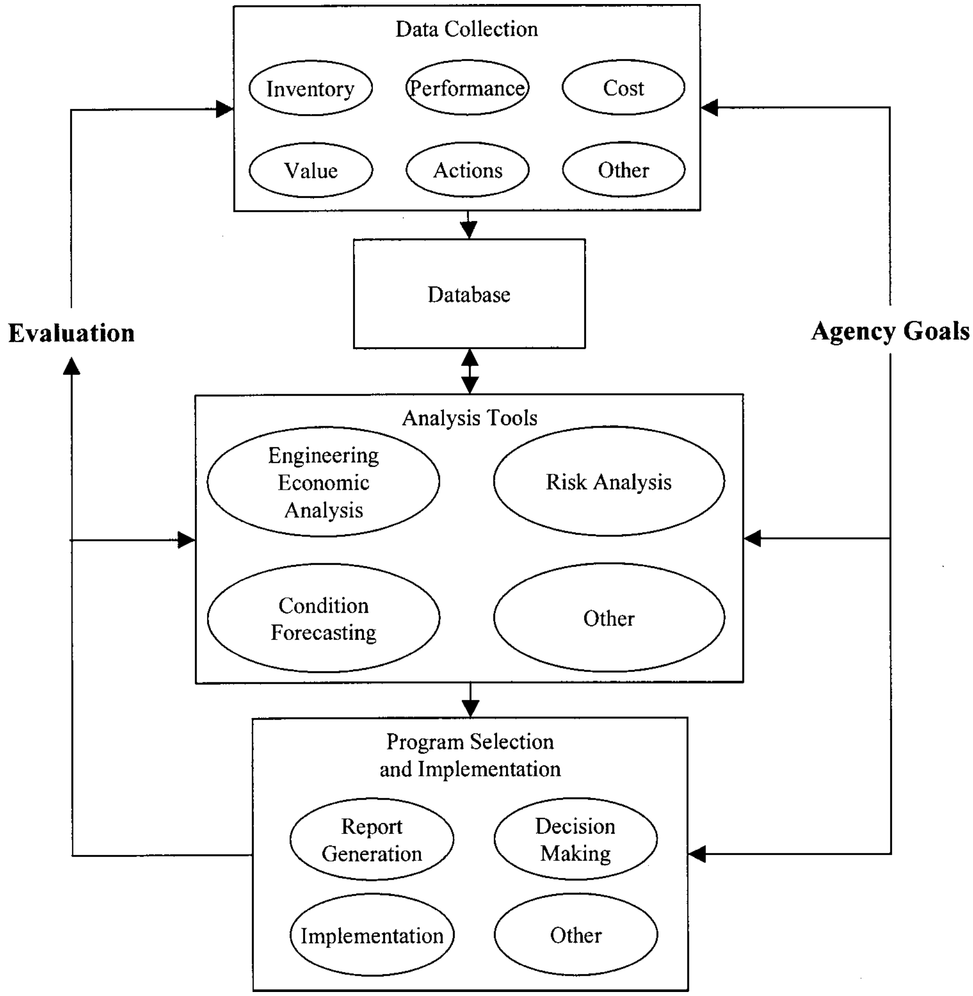

Fig. 2. Asset management system components

in which divisions are organized around a particular asset class, make trade-offs across asset classes virtually impossible in most existing systems (FHWA 1999).

Individual infrastructure management systems also tend to be geared toward the tactical rather than the strategic level; that is, the systems provide users with specific, implementable plans. These plans may be for the network level (a group of facilities such as all the pavements in a county), the project level (a particular facility, such as a bridge), or both. For example, a well-designed infrastructure management system should be able to calculate the expected impacts of performing a repair or rehabilitation activity now or later. Deferring activity may be a viable option, but the agency should be provided with an estimate of the cost of the decision. In terms of selecting remedial activities, a good system should be able to estimate the life-cycle costs associated with different activity levels. "Fully repairing" a site using the highest cost, highest reliability method may not always be the best option over the asset life. Rather, it may be more economically viable to apply a "quick fix" repeatedly, depending on the relative cost and reliability. An infrastructure management system should provide the capability to analyze these trade-offs.

An infrastructure management system is, among other things, a decision support system. System inventory and performance data are collected and analyzed, along with budget and cost information, to determine the best course of action to attain performance goals. The data collection and decision support modules are critical. As such, these systems can form the building blocks for practicing asset management.

Managing Geotechnical Assets

Although they have not been included explicitly in discussions of transportation asset management, geotechnical assets are critical to our transportation system functioning effectively. The following sections review the components of an asset management system, propose a framework for including geotechnical assets in asset management, and identify some of the issues that need to be addressed if geotechnical assets are to be managed systematically in conjunction with other transportation assets.

Components of Asset Management Systems

As discussed, Fig. 1 shows the generic framework for asset management proposed by the FHWA's Office of Asset Management (FHWA 1999). Fig. 2 shows a simplified framework with the basic components subdivided into particular activities or types of data. Fig. 1 presents a clearly divided, sequential flow-chart, while Fig. 2 shows a more conceptual grouping of functions. The boxes in Fig. 1 correspond loosely to the ovals in Fig. 2.

Data are central to a comprehensive asset management system, just as they are central to a management system for any particular type of infrastructure. Data include both ‘‘static’’ data—data that seldom if ever change, such as a location or date built—and ‘‘dynamic’’ data—data that change frequently or continually, such as measurements reflecting current condition. In addition, a variety of cost data is important. An agency should assign value to its assets, and past, present, and projected maintenance and rehabilitation costs should be tracked. Budget data and allocation constraints should also be tracked. All data should be stored in one or more databases that, ideally, are accessible and provide useful information to personnel throughout the agency.

Analysis tools apply algorithms to data extracted from the database to produce information that supports decision making. These tools include engineering economic analysis, risk analysis, condition forecasting, and other tools that use the agency goals as a guideline for determining appropriate use of resources. The tools answer questions about the future condition of assets under different funding allocation schemes within given budget constraints, appropriate actions to apply to particular assets, and potential costs and probabilities of unforeseen events.

The program selection and implementation function packages the information produced by the analysis tools so it will be useful to agency decision makers. This means that reports should contain different information in different formats for different classes of users. This information forms the basis of programming decisions and subsequent implementation. Finally, top management can use the information from the reports to determine whether the data collection practices and analysis tools are sufficient.

Framework for Geotechnical Asset Management

Current asset management systems (e.g., PMS, BMS, etc.) are essentially single entity management systems in the sense that a limited and specific type of asset is managed independently of other assets. Although some types of geotechnical assets (such as subgrades or foundations) may be addressed in PMS or BMS, others, such as slopes, are not (see Table 1 for classifications). Geotechnical assets are somewhat unique in the supportive role they play for other assets. As a result, effective geotechnical asset management (however geotechnical assets are defined) requires that ‘‘cross-asset’’ issues be addressed.

If Fig. 2 is examined in the context of geotechnical assets, more specific labels can be assigned to each of the components. Table 2 provides one possible mapping of geotechnical-specific assets to the general functions shown in Fig. 2. The table is not meant to be an exhaustive list of all aspects of the system, but rather an example of geotechnical specific components. Development of this mapping raised a number of issues within each category that must be addressed if geotechnical assets are to be integrated into an asset management system. The following sections describe these issues, as well as the mapping itself.

Agency Goals

It is unlikely that transportation agencies will set direct performance goals for geotechnical assets. Rather, the performance goals for geotechnical assets will arise out of performance goals for other ‘‘primary’’ assets. For example, a geotechnical-related goal might be to minimize funds spent on maintenance while minimizing failures that affect pavement structure. Since the geotechnical-related goals depend on the performance of other assets, geotechnical asset management must interact or be integrated with other ‘‘primary’’ asset management functions, as shown in Fig. 3.

Table 2. Mapping of Geotechnical Assets to Asset Management System Components

Asset management system component	Geotechnical-specific description
Agency goals	Agency unlikely to have specific goals for geotechnical assets
Data collection	
Inventory	Location, extent, height of embankment, soil properties, etc.
Performance	Existing erosion, stability, etc.
Cost	Maintenance budgets, cost of maintenance actions, etc.
Value	Several options available; replacement cost may be most appropriate
Actions	No action, monitor, temporary repair, permanent repair, etc.
Other	Impacts of failure (safety and mobility), etc.
Analysis tools	
Economic analysis	Calculate life-cycle costs to compare impacts of various maintenance and repair options, etc.
Risk analysis	Evaluate risk of repair alternatives as well as risk of no repair, etc.
Condition forecasting	Predict future condition of slope, embankment, etc., based on current and historical information, etc.
Other	Calculate level of hazard and factors of safety, etc.
Program selection and implementation	
Report generation	Tables, graphs, charts, etc.
Decision making	Compare costs, benefits, and risks of alternatives under different budget scenarios and choose course of action
Implementation	Allocate resources and conduct projects
Other	Suggest modifications to budget to achieve performance objectives
Evaluation	Evaluate whether data and analysis tools are providing useful information and whether goals are being met

Data Collection

Table 2 outlines several types of data that agencies will need in order to manage geotechnical assets effectively. Although some agencies collect some of the required data, many aspects of data collection will need to be improved if geotechnical asset management is to be implemented. First, few agencies currently maintain inventories of geotechnical problem sites (Hopkins et al. 1988; Turner and Schuster 1996), and we are not aware of any agencies that maintain complete inventories of geotechnical assets. Many agencies do not track maintenance division costs at the level of detail required to ascertain costs for geotechnical repairs. Furthermore, agencies seldom quantitatively assess the performance of repair measures with time once they are implemented, so it is difficult to utilize current assessments in an asset management approach. While these are important issues, agencies can build on the steps that have been taken in these areas with the RHRS and similar approaches described previously. Other issues related to data collection are more challenging.

Performance. Most agencies do not formally and quantitatively assess the condition of geotechnical assets on a routine basis.

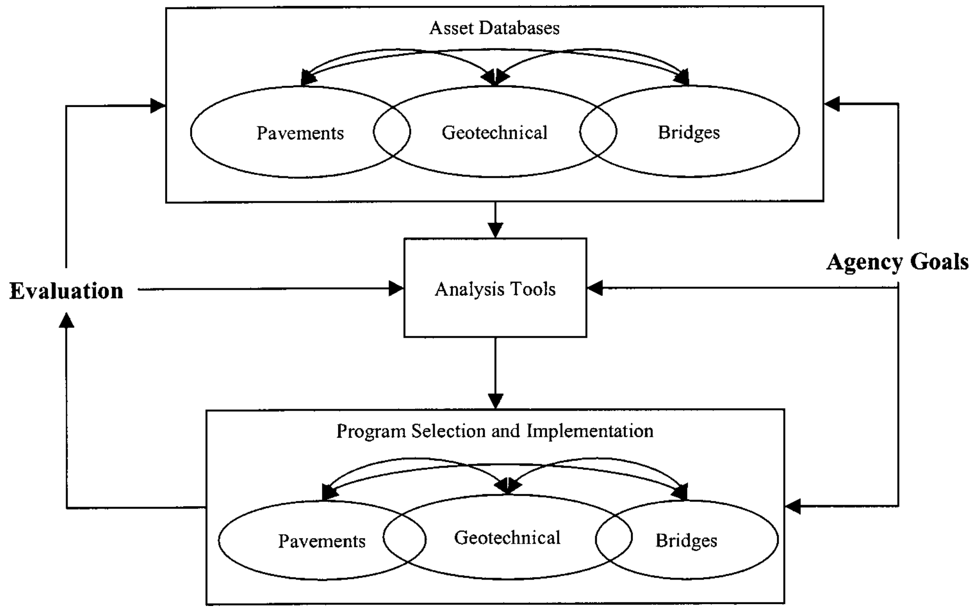

Fig. 3. Interaction of types of infrastructure in asset management

However, as demonstrated by PMS and BMS, effective management depends on knowledge and quantifiable measures of current condition, as well as other measures of current performance. Performance indicators, which may reflect physical condition, user cost, or other measures, are an essential component of any infrastructure or asset management system. It is important that the performance indicators be tied to the agency goals. More appropriate and comprehensive performance indicators must be developed for geotechnical assets.

Value. Although a variety of methods can be used to value physical assets, agencies have not applied these methods to geotechnical assets. One common method for valuing physical assets is to use replacement cost; that is, if the agency were to construct the facility today, how much would it cost? This method could be applied to geotechnical assets; it would likely include the value of the land itself plus the estimated material and construction costs in current dollars. However, given that the value of geotechnical assets to the transportation system is in how well they enable other facilities to function, this may not be the most appropriate valuation method. Unfortunately, valuation methods that consider the interaction among different forms of assets are not readily available.

Other. Another issue that must be addressed in data collection is identification of potential impacts of poor asset performance. Geotechnical failures can impact both the safety and mobility of the public. For example, a serious slope failure on a heavily traveled road would have significant impacts on the traveling public, whereas a minor failure would have a lesser impact. Consistent and quantifiable measures of potential consequences are needed in such cases to enable appropriate decision making. Several of the existing systems described previously include such measures, but additional work is needed in this area.

Analysis Tools

Table 2 identifies four major categories of analysis tools for geotechnical asset management: economic, risk, condition forecasting, and other. Engineering economic and risk analysis methods are used to support a variety of engineering decisions, and it is likely that these methods will serve as an integral tool for geotechnical asset management systems. Engineering economic analysis tools generally are well developed and widely accepted. Risk-based analysis methods, however, have been used only sporadically in geotechnical applications for a number of reasons, including lack of familiarity for geotechnical engineering professionals as well as difficulty in dealing with temporal and spatial variability of soil conditions (Duncan 2000). Nonetheless, in recent years, organizations such as the U.S. Army Corps of Engineers (USACE) have turned increasingly to risk-based decision making and reliability based design tools for facilitating management decisions (USACE 1999). This trend is expected to continue, as methods become better established and the geotechnical engineering profession becomes more comfortable with the shift in approach.

Reliability based analyses are the most logical choice for forecasting the future condition of geotechnical assets because they enable the life-cycle costs of very different types of conditions to be compared rationally. Conditions involving relatively low costs but with high probabilities of occurrence can be compared to conditions with relatively high cost but low probabilities of occurrence by weighting costs according to probability of occurrence. However, one issue that must be considered in reliability-based analyses is how to account for varying time horizons. A typical question that must be answered in an asset management framework is what are the costs and consequences of repairing an asset now versus repairing the asset in a year (or five years, ten years, the life of the structure, etc.). Current reliability based analysis tools and procedures for geotechnical assets are not generally well suited to such questions, although some progress has been made in recent work (Wolff 1996). Continued advancement in this area is required if effective and accurate analysis tools are to be available for implementation in an asset management framework.

Condition Forecasting. Condition forecasting, which is often based on deterioration models, has also seen little application to

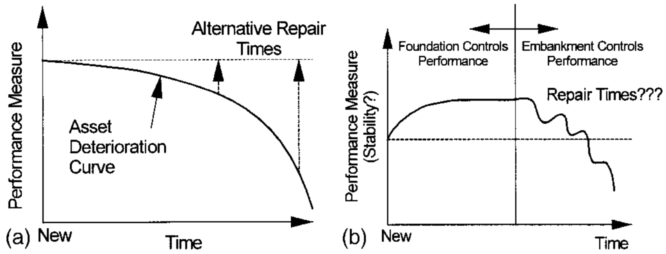

Fig. 4. Representative deterioration curves: (a) traditional pavement deterioration; (b) deterioration of embankment over soft foundation soils

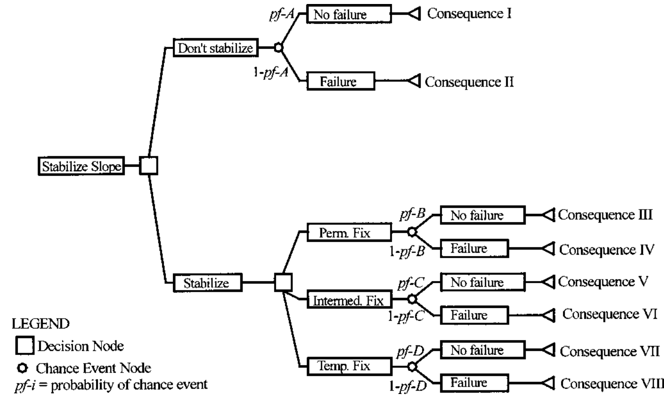

Fig. 5. Slope stabilization decision tree

geotechnical assets. The most notable work in this area to date is that by Wolff (1996). In the context of pavements, the goal of preservation is to ''reduce the rate of deterioration'' (FHWA 1999). One component of a pavement management system is an analysis of predicted future condition under different maintenance and rehabilitation scenarios. Pavements are generally assumed to deteriorate slowly at first, and then the rate of deterioration accelerates as the pavement ages, as shown in Fig. 4(a). As the condition worsens, the cost to return the pavement to ''new'' condition (or another target condition) increases, as does the uncertainty in predicting the actual condition. An appropriate maintenance strategy, then, is to try to maintain the pavement so that it never drops into the bottom portion of the curve.

The deterioration model shown in Fig. 4(a) may not capture all aspects of performance decline for geotechnical assets. Since the performance of geotechnical assets is often dominated by random events, such as extreme rainfall, abrupt changes in condition may occur at any point in the life cycle. Furthermore, the condition of some geotechnical assets may actually improve over time. An example of this phenomenon is embankments on soft foundation soils, which generally become more stable over time until the foundation soils are fully consolidated [Fig. 4(b)]. At this point, the embankment stability takes over as the governing factor in performance. On the other hand, the classical deterioration models [Fig. 4(a)] may forecast progression of problems like erosion or geosynthetic clogging reasonably well.

Other. Another issue that must be considered in the analysis of alternatives is the maintainability of various types of geotechnical assets. Some geotechnical assets, such as foundations, are essentially ''unmaintainable.'' That is, there are no available methods for performing midlevel rehabilitation; any significant action requires reconstruction or additional construction. With other geotechnical assets, such as embankments, this is not a problem.

Finally, analysis tools could improve decisions regarding future construction. Many decisions made during design and construction will significantly impact the life-cycle costs, and hence the ''value,'' of the asset. Using a highway embankment as an example, the slope angle, height, and materials selected during design and the construction quality in the field affect the initial construction costs. These parameters also affect the required maintenance over the life of the embankment. A conservatively designed slope will tend to require more right-of-way, more or better material, and perhaps modification or improvement of existing ground, all of which will increase construction costs. However, a conservatively designed slope is expected to require less lifetime maintenance than a less conservative design.

Program Selection and Implementation

It should be possible to apply program selection and implementation algorithms currently used in existing systems to geotechnical assets without significant modifications. One additional consideration related to geotechnical assets exists because there is unlikely to be a separate budget for maintaining geotechnical assets. Consequently, decisions must be made considering the costs and benefits of potential repairs to other types of assets.

Implementation of Geotechnical Asset Management

While many issues remain to be addressed, the basic tools for geotechnical asset management are available. The next section presents one possible method of implementation for geotechnical asset management that includes the interaction with other agency assets (an example of how asset interaction can be incorporated). The second section outlines several steps an agency can take to incorporate geotechnical infrastructure into its asset management program.

Implementation Framework for Slope Stabilization Decision

One approach to implementing the analysis portion of the framework is to use decision analysis to evaluate the alternative courses of action for managing slope repair decisions. A decision tree is one tool for this type of analysis (Clemen 1996). A decision tree structures the components of a decision and allows a quantitative evaluation of the best outcome based on the uncertainties and consequences associated with each choice.

Fig. 5 shows a simple decision tree for evaluating what action to take in response to a failure of an earth embankment or slope. The principal decision is whether to stabilize the slope. If the decision is made to stabilize the slope, one of several alternative stabilization measures could be selected. These alternative measures may stabilize the slope with varying degrees of success or for different lengths of time, and their costs will differ. Each alternative will also have varying probabilities of success or failure depending on the particular case in question.

To evaluate the decision tree, it is necessary to know the probabilities and consequences associated with each of the branches. The probabilities of each branch can be determined in a number of ways. Perhaps the simplest way would be to use historical data to establish the frequency of success/failure of alternative repair measures. However, given that record-keeping practices for these activities typically are poor, this alternative currently is not feasible (although it may become so in the future). Expert solicitation (i.e., judgment) could also be used, although there is clear potential for bias and questionable experts. Perhaps the best means currently available for evaluating the probabilities is to perform reliability based analyses of the alternative stabilization measures. As mentioned previously, these types of analyses are becoming more commonly used in the geotechnical engineering profession and can serve as a sound basis for decision making.

The probabilities for each alternative course of action in Fig. 5 are essentially independent of other assets. These probabilities can also be determined without a vast amount of data aside from physical characteristics (e.g., geometry, soil properties, anticipated loads, etc.). In contrast, the consequences for each decision path are intimately tied to other assets and the agency goals. In fact, it is the consequences for each path that link the geotechnical assets with the performance of other assets.

Agency goals should form the basis for measuring the consequences. In the simplest form, consequences used in the decision tree could be purely economic. In this case, the decision tree must include at least three different types of costs. The first type of cost is associated with bringing the site from its current state to an acceptable condition. These costs may be for repairing guardrail, patching pavement, repairing or clearing drainage structures, etc. Some of these costs will have to be incurred regardless of what course of action is selected, although costs for a specific activity may differ for different courses of action. The second type of cost is associated with stabilization of the slope. These will be the direct and indirect costs associated with design and construction of the stabilization measure. The final type of cost is associated with a potential future failure and subsequent repair of that failure. Such costs should obviously be weighted according to the probabilities of future failures occurring. Once the costs associated with each of these sources are determined, the overall consequence of each alternative is determined by summing up the individual costs with appropriate consideration given to the time value of money. At this point, the decision tree can be solved to determine the best course of action.

Unfortunately, this simplistic consideration of consequences neglects many of the real consequences that should impact the decision. Examples of issues that are neglected in this simple approach include user safety and the level of hazard for the slope, user costs associated with performing the repair, and potential impacts to other agency assets (e.g., pavements, bridges, culverts, etc.). Although methods for incorporation of such consequences within the decision framework are not well developed, existing ‘‘hazard rating’’ systems that include consideration of these issues for soil and rock slopes provide a starting point.

The example described here is simple, and many additional consequences and courses of action could be included in the decision tree. One potential addition would be to consider monitoring and/or instrumenting the site to gather additional information about whether the slope should be stabilized and how it might best be stabilized. Such monitoring has the benefit of reducing uncertainties about the particular slope being monitored (thereby potentially changing the decision) and, in addition, would provide data to improve deterioration models utilized in the analysis tools described previously (which has some inherent value). Another possibility is to expand the decision tree to include additional stabilization alternatives. There is also an issue of time/decision context, in that selection of a short-term stabilization measure would likely lead to reanalysis of the problem at a later date, in which case a recursive type of decision would have to be considered. A similar approach can be utilized for other geotechnical assets such as retaining structures.

Steps toward Implementation

The decision tree described provides a specific example of how decision analysis might be incorporated in geotechnical asset management. However, effective implementation begins at a higher level. The following list provides some suggestions for incorporating geotechnical assets into an agency’s asset management program:

- Assess agency goals and objectives to determine how geotechnical asset management can support high-level agency goals. These goals and objectives typically relate to meeting user expectations for service provision. For example, the Missouri Department of Transportation’s long-range transportation direction (MoDOT 2001) articulates eight primary goals relating to safety, maintenance, congestion relief, and economic and social concerns. The most obvious link between geotechnical asset management and these goals falls under maintenance. We are working to make this connection explicit and to ensure that other supporting functions are not overlooked.
- Assess current systems used and identify overlaps between existing systems and geotechnical assets. Agencies should assess the capabilities and extent of use of any existing infrastructure management systems, such as PMS and BMS, as well as any landslide, rockfall, or other geotechnical hazard management systems within the agency. The agency should focus on whether and what types of geotechnical features are included in existing systems (for example, does the pavement management system include subgrade information?).
- Build on and integrate with existing systems. An agency needs to determine whether systems can be extended and what data are required. As discussed, in many cases partial inventories exist. Agencies should take advantage of prior investments and work to extend the databases and analysis tools used.
- Make sure that the information is passed back and forth between systems. As an example, if the geotechnical decision maker decides to select a marginal or temporary stabilization measure, it is important that the pavement decision maker not decide to construct a new, high tech (expensive) pavement system (or at least to be aware of and consider the potential ramifications of the slope decision).

Summary and Directions

Interest in asset management continues to increase. Although component infrastructure management systems, such as those for pavements and bridges, exist, the integration of geotechnical assets is essential if the systems are to minimize life-cycle costs and maximize life-cycle performance.

Although the rationale for geotechnical asset management is clear, the steps for implementation are less obvious. This paper identifies issues raised in considering implementation and suggests how many of them can be addressed. The geotechnical asset management components presented in Fig. 2 and Table 2 differ in their stages of development. While not all of the necessary data are available, some of the data exist, and steps for completing the database are relatively straightforward. Similarly, it should be possible to adapt the program selection tools that have been developed for other types of infrastructure to geotechnical assets.

Greater challenges exist with agency goals and analysis tools. From a policy perspective, geotechnical asset management must be tied explicitly to agency goals. However, since agency goals typically are focused on transportation-specific issues, the connections are more difficult to articulate. From an engineering perspective, developing analysis tools for geotechnical assets, particularly for performance modeling, will require substantial effort. However, given the well-documented, positive impacts achieved to date for existing asset management systems, and the high costs currently incurred by agencies for maintenance and repair of geotechnical problems, the effort required to incorporate geotechnical assets into these systems seems justified.

Acknowledgments

The writers are grateful to the Midwest Transportation Consortium and the Missouri Department of Transportation for their support of this project. The opinions, findings, and conclusions expressed in this publication are not necessarily those of the Department of Transportation, Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

References

Adams, T. M., Hendrickson, C., and Christiano, P. (1988). ''Expert system architecture for retaining wall design.'' *Transportation Research Record 1187*, Transportation Research Board, Washington, D.C., 9–20.

Clemen, R. T. (1996). *Making hard decisions: an introduction to decision analysis*, 2nd Ed., Brooks/Cole Publishing Company, Pacific Grove, Calif.

Cowe Falls, L., Haas, R., McNeil, S., and Tighe, S. (2001). ''Using common elements of asset management and pavement management to maximize overall benefits.'' *Transportation Research Board 80th Annual Meeting Preprint* (CD-ROM), Transportation Research Board, Washington, D.C.

Duncan, J. M. (2000). ''Factors of safety and reliability in geotechnical engineering.'' *J. Geotech. Geoenviron. Eng.*, 126(4), 307–316.

Federal Highway Administration (FHWA). (1997). *Proc., Asset Management: Advancing the State of the Art into the 21st Century through Public-Private Dialogue*, Washington, D.C.

Federal Highway Administration (FHWA). (1999). *Asset management primer*, Office of Asset Management, Washington, D.C.

Federal Highway Administration (FHWA). (2001). ''U.S. Transportation Secretary Mineta announces initiative to develop first-ever national tunnel management system.'' ⟨http://www.fhwa.dot.gov/pressroom/fhwa0126.htm⟩ (July 19, 2001).

Fish, M. F., and Lane, R. M. (2002). ''Geographic information system and New Hampshire rock cut inventory.'' *Transportation Research Board 81st Annual Meeting Preprint* (CD-ROM), Transportation Research Board, Washington, D.C.

General Accounting Office/Resources, Community, and Economic Development Division (GAO/RCED). (1997). ''Transportation infrastructure: states' implementation of transportation management systems.'' *Rep. GAO/RCED-97-32*, Washington, D.C.

Hadjin, D. J. (2002). ''New York State Department of Transportation rockfall hazard and risk assessment.'' *Transportation Research Board 81st Annual Meeting Preprint* (CD-ROM), Transportation Research Board, Washington, D.C.

Ho, C. L., and Norton, S. S. (1991). ''Development of an unstable slope management system.'' *Rep. WA-RD 270.1*, Washington State Department of Transportation, Olympia, Wash.

Hopkins, T. C., Allen, D. L., Deen, R. C., and Grayson, C. G. (1988). ''Highway slope maintenance and slide restoration workshop: participant manual.'' *Rep. No. FHWA-RT-88-040*, Federal Highway Administration, Washington, D.C.

Hopkins, T. C., Beckham, T. L., Sun, C., Ni, B., and Pfalzer, B. (2001). ''Development of a geotechnical database.'' *Transportation Research Board 80th Annual Meeting Preprint* (CD-ROM), Transportation Research Board, Washington, D.C.

Klinedinst, G., Munoz, A., and Niessner, C. W. (1986). ''Guidelines for slope maintenance and slide restoration.'' *Rep. No. FHWA-TS-85-231*, Federal Highway Administration, Washington, D.C.

Kuhne, J. (2002). ''Rockfall hazard rating: North Carolina Department of Transportation reexamines an abandoned project.'' *Transportation Research Board 81st Annual Meeting Preprint* (CD-ROM), Transportation Research Board, Washington, D.C.

McKay, D. T., Rens, K. L., Greimann, L. F., and Stecker, J. H. (1999). ''Condition index assessment for U.S. Army Corps of Engineers civil works.'' *J. Infrastruct. Syst.*, 5(2), 52–60.

McNeil, S., Tischer, M. L., and DeBlasio, A. J. (2000). ''Asset management: what is the fuss?'' *Transportation Research Record 1729*, Transportation Research Board, Washington, D.C., 21–25.

Missouri Department of Transportation (MoDOT). (2001). ''MoDOT's long-range transportation plan.'' ⟨http://www.modot.state.mo.us/lrtd/pdf/lrtd-web.pdf⟩.

Oregon Department of Transportation (ODOT). (2001). *ODOT Landslide and Rockfall Pilot Study Final Rep.*, ODOT Geo-Hydro Section, Salem, Ore.

Pierson, L. A., and Vickle, R. V. (1993). ''Rockfall Hazard Rating System, participant's manual for NHI course 130220.'' *Rep. FHWA SA-93-057*, U.S. Department of Transportation, Washington, D.C.

Turner, A. K., and Schuster, R. L., eds. (1996). ''Landslides: investigation and mitigation.'' *TRB Special Rep. 247*, Transportation Research Board, Washington, D.C.

U.S. Army Corps of Engineers (USACE). (1999). ''Risk-based analysis in geotechnical engineering for support of planning studies.'' *Rep. ETL 1110-2-556*, Washington, D.C.

Wolff, T. F. (1996). ''Application of time-based reliability analysis to Corps of Engineers' geotechnical engineering problems.'' *Final Rep. Prepared for the St. Louis District, U.S. Army Corps of Engineers*, Shannon and Wilson, Inc., St. Louis.